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# First Measurements with NeXtRAD, a Polarimetric X/L Band Radar Network

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**Abstract**—NeXtRAD is a fully polarimetric, X/L Band radar network. It is a development of the older NetRAD system and builds on the experience gained with extensive deployments of NetRAD for sea clutter and target measurements. In this paper we will report on the first measurements with NeXtRAD, looking primarily at sea clutter and some targets, as well as early attempts at calibration using corner reflectors, and an assessment of the polarimetric response of the system. We also highlight innovations allowing for efficient data manipulation post measurement campaigns, as well as the plans for the coming years with this system.

## I. INTRODUCTION

Multistatic radar systems have been investigated in the radar community for a number of years. These systems consist of multiple transmitter and receiver nodes, in order to take advantage from the diversity, in both target and clutter returns, which is obtained by varying the system geometry. This can offer potential advantages over conventional monostatic radar, such as enhanced target signatures and improved detection using multi-perspective views, and the fact that the receive-only passive nodes are less complex and more compact, hence suitable to be mounted on UAVs or other unmanned platforms for enhanced surveillance operations [1], [2].

The advantage of having multi-perspective views on the targets of interest and the possibility of modifying the deployment geometry if mobile nodes are available can be particularly beneficial for the identification, tracking, and classification of small maritime targets such as small boats, inflatables, and periscopes. However, there are very limited available bistatic and multistatic sea clutter data, as the required systems and measurements to collect them are complex and often related to classified research. A significant challenge is posed by the need of synchronising different nodes to the same, common phase reference to achieve coherency and good Doppler performance, even when the nodes are separated by baselines in the order of hundreds of metres or a few kilometres.

Coherent networks of sensors are becoming feasible, and the advantages of these sensors over conventional, monostatic radars needs to be fully understood. This requires a set of models for target and clutter measured by these new sensors,

so that performance of these systems can be assessed during design.

One of the key objectives of this paper is to present the NeXtRAD as a tool for collaboration in the area of networks of fully polarimetric radar to understand the underlying characteristics of clutter and targets when measured multistatically. The system is to be configured to be deployed in the open from small, self-contained, rugged, cabinets.

In this paper we will present the latest measurements with the new NeXtRAD system, based on field trials in Simon's Town (clutter and small targets) in December 2016. We also present the measurements made during laboratory integration of the system, as well as low power field measurements.

This paper starts with a review of the objectives of the system [2]. This is followed by a description of the system configuration (three nodes, one active, two passive) and the plans to calibrate it. We then present measurements already made during the development and preliminary testing phase, to be followed by the results from the December 2016 trials. The paper concludes with the proposed programme for the system over the following 5 years.

## II. NEXTRAD OBJECTIVES

A rationale for the NeXtRAD dual-band multistatic radar network, developed by University College London (UCL) and the University of Cape Town (UCT) was presented [2]. This radar is the successor to the NetRAD S-band system which was conceived as a flexible, low-cost testbed to make measurements of bistatic target and clutter signatures and to explore the issues of practical multistatic radar. In its initial form NetRAD consisted of a three-node network with a transmit power of +23 dBm. The nodes were connected by cable for control and synchronisation, with a maximum cable length of 200 m.

In 2010/11 NetRAD was upgraded to provide 500 W transmit power and to remove the need for physical connection of the nodes, by using GPSDOs at each node and wireless links from the master node to each of the other nodes [3]. These modifications significantly increased the achievable range, and allowed much greater node separation. The key attribute of

NetRAD is that it allows simultaneous measurement to be made of monostatic and bistatic signatures, and hence a direct comparison to be made. In this form NetRAD was used in trials in South Africa to make measurements of bistatic sea clutter and small maritime target signatures, and led to the important conclusion that bistatic sea clutter may be less “spiky” than the equivalent monostatic clutter [4]–[11].

NetRAD has also been used for measurements of the radar signatures of the microDoppler of human targets[12], wind turbines[13] and drones and birds [14], [15]. The experience gained with NetRAD has been incorporated in the design of the next-generation NeXtRAD radar, described in this paper. This is a three-node, dual-band (X-band and L-band) polarimetric multistatic radar. It has been designed to be more flexible, user-friendly and reliable.

### III. SYSTEM CONFIGURATION

#### A. High Level Description

The system is comprised of a single active node and two passive nodes illustrated in Figure 1. All three nodes are equipped with GPS disciplined oscillators [16] which supply a stable 100 MHz reference clock to the digital and RF transceivers. Critical subsystems in each node can be monitored and controlled by a laptop computer. These three node computers are connected by WiFi links to a central command and control laptop, which distributes an experiment header file to each node. Motorized pedestals equipped with GPS positioning software direct all antenna beams to a common target, which can be moving and instrumented with GPS and a data link. Video recordings of the target scene are recorded by video cameras mounted on each receiver pedestal, providing a visual reference of the target scene during a measurement.

#### B. Digital Backend and REX

Conversion between radio frequency and the 125 MHz intermediate frequency is done by an RF transceiver system supplied by Reutech Radar, known as the Radar Exciter (REX). The Pentek Model 71621 software radio interface was procured for use as the digital transceiver in the active node of the radar. This module is equipped with three 16-bit ADC channels, and a 16-bit DAC output. Identical units are used in the passive nodes in receive-only mode.

A low power (below 24 dBm) prototype of the active node was built to test the digital transceiver, REX, X- and L-band antenna prototypes (see Section IV-A), and frequency distribution units June 2016. Subsequent tests in November 2017 used medium power transmitters of 10 W and 3 W for L- and X-band respectively.

#### C. Database Management and Real Time Processing

The raw radar data and corresponding ancillary data (e.g. video, audio, GPS, time, weather, sea state, log files) are stored in a Hierarchical Data File version 5 (HDF5) archive. They are stored in the untouched form so that they do not include any irreversible processing by-products. The keywords of the combined data are extracted and entered in to a relational

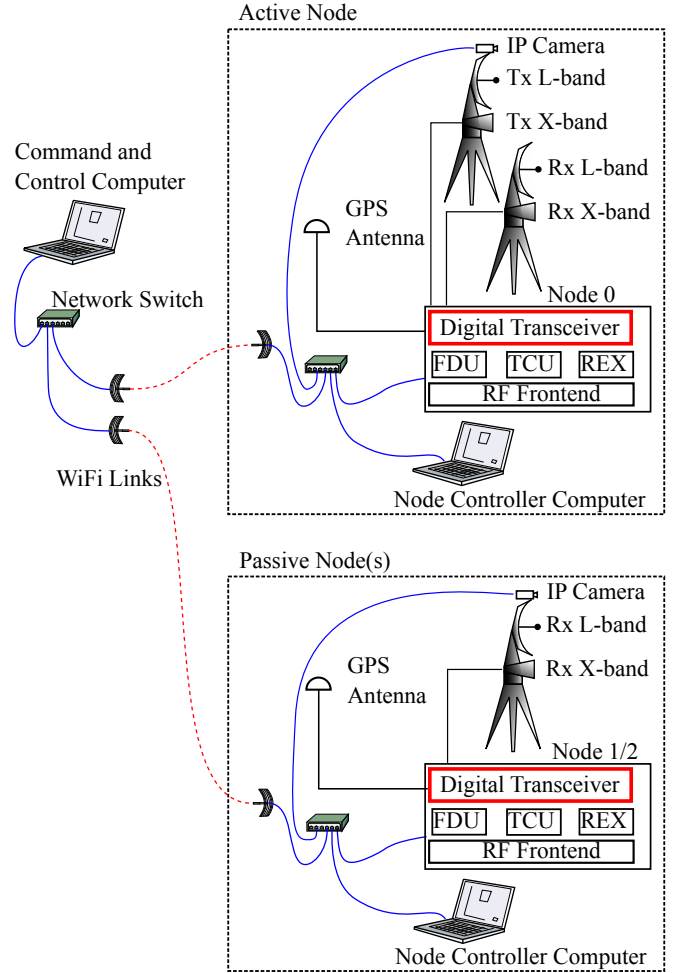


Fig. 1. The NeXtRAD system’s configuration, showing an active/passive pair.

database, in this case MySQL has been used. The database can then be used to search for specific characteristics or for common attributes.

A PHP web interface is planned for the future to make querying the database easier. A GPU pulse compressor has been developed to process the radar data further.

The recorded data are saved in binary format as sequential, 16-bit samples. Each range swath typically contained 2048 complex range samples, under a pulse repetition frequency of 1 kHz. Each range line would therefore need to be processed in under 1 ms if real-time plots are to be produced.

A quick-look processor was developed at UCT using popular freeware; FFTW and OpenCV. Using an off-the-shelf Intel i5-3750, real-time generation of range-time-intensity (RTI) and range-Doppler plots was achieved. A 60 s recording is processed in under 10 s, significantly surpassing the real-time requirement, using the parameters outlined in Table I. The processor was tested using NetRAD data. The slow-quick time plot is shown in Figure 2.

A multi-threaded version of the quick-look processor has been developed for NetRAD datasets and has been tested on

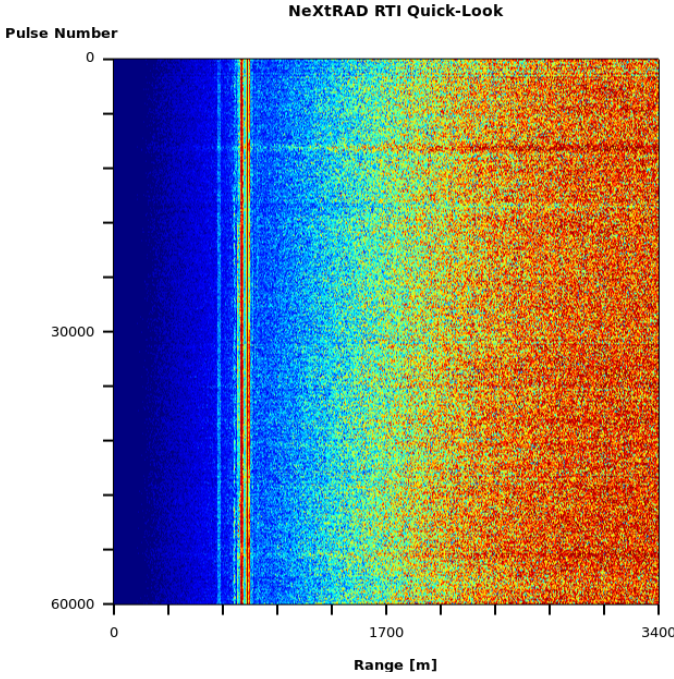


Fig. 2. Sample RTI Quick-Look using NetRAD data (S Band).

a compute-oriented Amazon Web Services (AWS) instance. This provided a more than  $10 \times$  acceleration over the single-threaded implementation for large datasets, as shown in this paper. We intend to upgrade the NeXtRAD quick-look processor to a multi-threaded implementation and achieve a similar  $10 \times$  speed-up. The convenience of having data and processing available publicly seems very attractive.

TABLE I  
PRINCIPAL SET OF PROCESSING PARAMETERS.

Parameter	Value
Range Lines in Data Set	60000
Complex Samples per Range Line	2048
Doppler FFT Size	128
Plot Updates during Processing	100

#### IV. CALIBRATION PLANS

##### A. X- and L-Band Antennas

The design and development of a dual polarised X-Band conical horn antenna (Figure 3a) and an L-Band parabolic dish antenna (Figure 3b) with centre frequencies of 8.5 GHz and 1.3 GHz respectively, with azimuth beamwidths of  $10^\circ$  for both polarisations. The X-Band antenna is required to handle a peak power of 400 W while the L-Band antenna must be capable of 1.6 kW, as well as low windage to allow mounting on a tripod.

An off-the-shelf antenna meeting the aforementioned specifications was either not available or unaffordable, and this has led the development of the antennas. The manufactured X-Band antenna prototype was found to have an azimuth HPBW

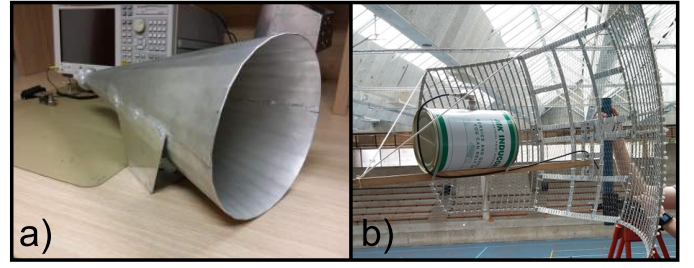


Fig. 3. Dual polarised antenna prototypes. a) X-Band conical horn antenna. b) L-Band parabolic dish antenna.

of  $9.1^\circ$  and  $10.4^\circ$  when horizontally and vertically polarised respectively. Similarly, the manufactured L-Band prototype antenna was found to have an azimuth HPBW  $13.9^\circ$  and  $12.4^\circ$  when horizontally and vertically polarised respectively. Detailed design procedure for X- and L-Band antennas are found in [17], [18] respectively.

##### B. Calibration Plans

Imbalances and distortions exist in the radar system due to polarisation coupling, and power leakage between the orthogonal channels as well as between the nodes [19]. The distortions in the radar system can be found through the use of passive calibration targets. Calibration techniques are applied to find the distortion matrices, co- and cross-talk imbalances, isolation errors and phase errors. These distortions can be removed or minimized to correct the errors and non-idealities introduced by the antennas [20].

The triangular trihedral corner reflector is chosen for the initial monostatic measurements for NeXtRAD. The corner reflector provides large RCS but is very sensitive to radar alignment. The collected data can be analysed and calibration techniques can be performed to remove impurities in the data. Metallic spheres or cylindrical tubes are suitable for bistatic and multistatic measurements due to insensitivity to radar alignments but has low RCS compared to corner reflectors.

Alternatively, it is possible to build an active radar calibrator that provides the flexibility in configuring the bistatic angle and polarisation alignment. Active calibrators will not be implemented for the first NeXtRAD measurements.

#### V. MEASUREMENTS

The NeXtRAD radar system has been preliminary tested in the laboratory at the University of Cape Town. Initially self-loop tests using a long section (200 m) of cable were performed to verify the effect of changing parameters of interest such as PRF and pulse length, as well as the phase stability in the Doppler domain through long recordings. Afterwards, additional tests were performed by locating the radar on the roof of the Department of Electrical Engineering at UCT and observing targets of interest such as cars and pedestrians in a nearby car park. X-band conical horn antennas described in Section IV-A were used to record one minute of data using a 50MHz bandwidth,  $0.6 \mu\text{s}$  pulses at a 1 kHz PRF on an 8.5 GHz carrier. A pedestrian target at approximately



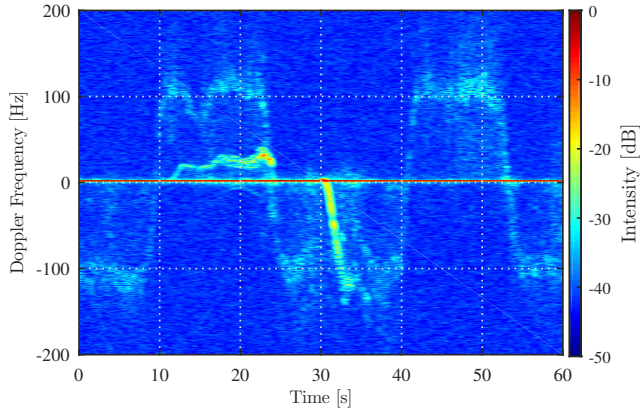


Fig. 4. A 60 second time-Doppler plot of pedestrian target taken at a 1 kHz PRF at X-band with the active node low-power prototype. Visible between 10 and 35 seconds in this plot is a strong return from a car moving out of a parking bay in the same area.

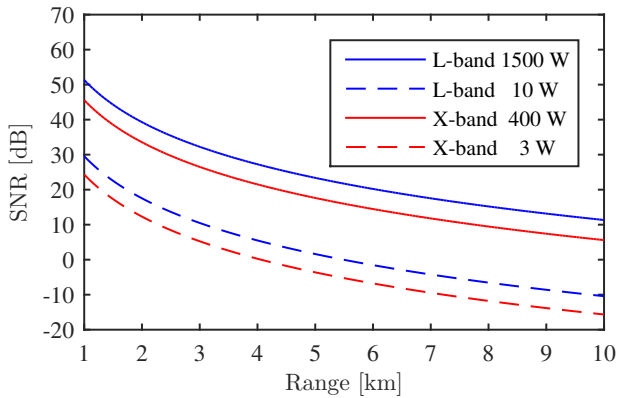


Fig. 5. Single pulse range vs SNR for a  $1 \text{ m} \times 1 \text{ m}$  cylindrical target with standard system parameters using a 10 W and 1500 W L-band transmitter, and a 3 W and 400 W X-band transmitter.

75 m range was detected by doppler shift, as seen in Figure 4. These experiments have demonstrated the capability of the NeXtRAD radar to capture range-time and Doppler signatures of these targets.

Plots of the single-pulse range vs SNR using both of these transmitters is shown in Figure 5. The modeled target is a 1 m radius, 1 m height metallic cylinder. Usable monostatic and bistatic calibration measurements were acquired with this modest transmitter power.

The key objectives for the NeXtRAD December 2016 measurement campaign were to gather multiband (L and X) dual polarized (at X-band) sea clutter data recorded over a series of azimuth angles and ranges, with respect to the wind and wave direction. The system was deployed on the roof of the South African Institute for Maritime Technology (IMT) building in Simon's Town. From this site, there was a clear 180 degree of view over False Bay which enabled us to obtain data across a wide range of geometries. The scenario was a littoral environment and is not necessarily be representative

of an open sea, but this data will still be useful for the sea clutter research community. The deployment location along with a series of example data capture geometries can be seen in Figure 6. Meta data on the wind and wave conditions were recorded using local weather stations and buoys at sea. In particular, measurements were taken in monostatic geometry, by varying the azimuth pointing direction from 358 deg then rotating clockwise to 58 deg, with a step of 10 deg. An interesting dataset was recorded on December 13, with high sea state conditions and a wind speed of about 20 knots. The transmitted signal was a LFM chirp with 50 MHz bandwidth and  $3 \mu\text{s}$  pulse length, modulated at three different carrier frequencies, 1.3 GHz (L), 8.5 GHz (X1) and 9.2 GHz (X2). A Pulse Repetition Frequency of 1 KHz was used, and the total recording time was 120 s, giving datasets of 120000 pulses. Figure 7 and 8 show the Range-Doppler maps of sea clutter data collected at an azimuth angle of 48 degrees, horizontal polarization and a carrier frequency of 8.5 GHz and 9.2 GHz. Range-Doppler maps were computed by using the average periodogram method, with windows of 256 pulses, normalizing the spectrum values on the maximum. Both figures show the zero-Doppler return from a static target located at about 1800 m from the radar, which is a lighthouse located on the top of a small rock in the sea. For the data collected at lower carrier frequency (Figure 7), the clutter spectrum is included between 300 m and 800 m in range and between 0 and -100 Hz in Doppler, with an average clutter-to-noise-ratio (CNR) of about 15 dB, and a peak of about 20 dB at a range of 400 m. Data collected at higher carrier frequency (Figure 8) show a similar sea clutter spectrum, with a slightly smaller CNR, approximately 12 dB. The presence of datasets collected at different carrier frequencies offer the opportunity to evaluate their impact on the sea clutter properties.

Measurements taken in this style include the CSIR 2007 X-band database[21] that was generated from a position on Signal Hill, Cape Town. This dataset has proven to be a very useful asset for the research community and the goal of our measurement campaign is to expand on this using the additional degrees of freedom of frequency band and polarimetry. In order to allow for a close comparison of the X and L band measured data the antennas will have the same beamwidth such that the illuminated patch is of comparable size in both cases. The main focus of the measurement campaign will be on sea clutter recordings, although additional target measurements may be taken at the time.

Within the configurable digital backend of the NeXtRAD radar node is a flexible arbitrary waveform generator (AWG) built into the Pentek ADC/DAC card. This will allow us to investigate the effects of waveform diversity on the sea clutter measurements that we take. Re-configuring both the waveform used and the central frequency of the system can be performed on a measurement-to-measurement basis. One of the interesting results that we would like to observe is the effect of range side-lobes from the match filtered pulse on the observed amplitude statistics of the sea clutter.

A further use of the AWG will be to transmit encoded data

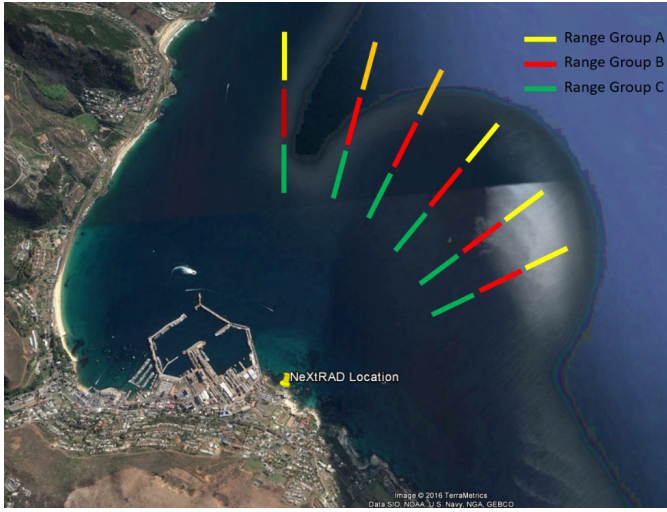


Fig. 6. NeXtRAD Deployment and measurement geometry.

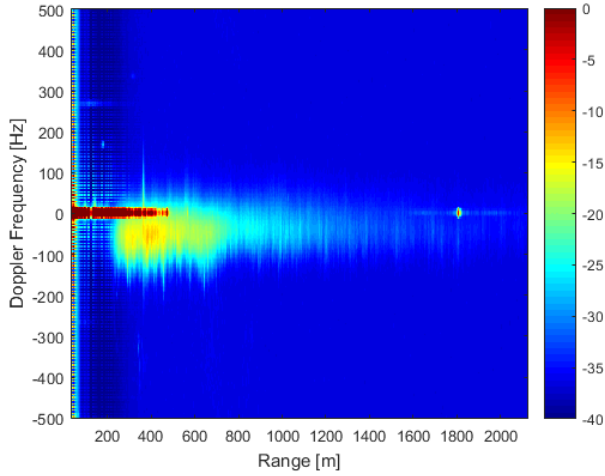


Fig. 7. Range-Doppler map of sea clutter data, collected at an azimuth angle of 48 degrees, 9.2 GHz carrier frequency, horizontal polarization .

to produce a 50 MHz noise like spectrum, and then test the reception and decoding of the data. This forms a symbiosis between the radar and a telecommunications system.

## VI. PROGRAMME

The system has been tested at low power (see Section V). The supporting subsystems (data network between nodes, positioners, sound and video recording, L and X band polarimetric antennas, timing and frequency control within a node, and between nodes have all been tested and verified. Work now focused to move from the 3 W X Band and 20 W L Band power stages to higher power amplifiers to extend the detection range. The capability of following targets with low radial angular velocity, where the target is instrumented with GPS and a telemetry link has been successfully tested. The current antenna mounts are optical telescope mounts, not intended for high speed angular motion.

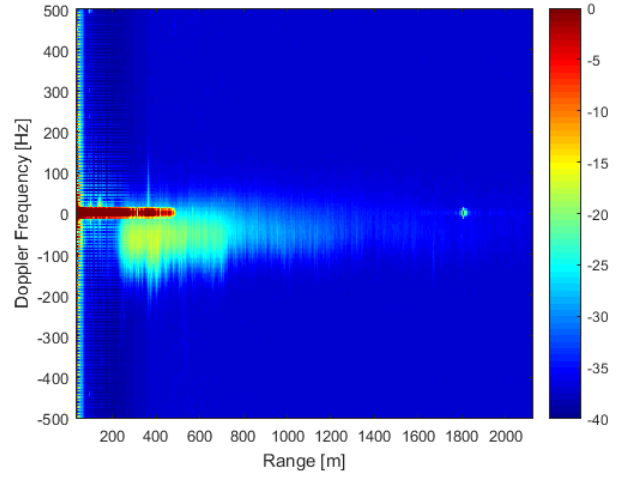


Fig. 8. Range-Doppler map of sea clutter data, collected at an azimuth angle of 48 degrees, 8.5 GHz carrier frequency, horizontal polarization .

The system was deployed at the Institute for Maritime Studies in late November 2016, with a mostly monostatic set of sea clutter measurements being made at L and X Band, including polarisation variations (Section V in the first two weeks of December 2016). During these tests, we also evaluated the receive only nodes, albeit in a quasi monostatic configuration.

During the first quarter of 2017, the high power stages (1.5 kW at L Band and 400 W at X Band) will be integrated and some measurements repeated. The passive nodes will be integrated and first multistatic trials will be carried out. We will also address multistatic, polarimetric calibration, which is a difficult technical problem, and active calibrators seem to offer a flexible solution.

The system needs to be able to be deployed easily, and towards the end of 2017 the system will be decommissioned and rebuilt into quasi hermetic cabinets to allow for deployment close to the seaside for long periods while gathering data. Prototype enclosures with heat exchangers have been tested successfully.

We would like to encourage users world wide to use the system either in South Africa, or, transported to other sites. The complexity of the system will mean at least one support person will have to be available, and operators will need to be trained. Hopefully this can be carried out collaboratively between the IMT and other potential users. Sharing of data and results should result, but can, of course, be protected by an appropriate joint agreement.

## VII. CONCLUSIONS

A successor to the S Band NetRAD has been described. We show that the low power loop back tests have been successful, achieving close to the 3 m pulse resolution expected of a 50 MHz linear chirp. The waveform generators are completely programmable, so experimentation of pulse to pulse modulation changes can be accommodated. We then go on to describe

the trials performed in December 2016 when medium power amplifiers were integrated (3 W and 10 W at X and L Bands). These tests were mostly monostatic, and conducted from the IMT building in Simon's Town, with Roman Rock lighthouse as a fiduciary target.

Plans for 2017 include mid year, full power tests in Simon's Bay, with the equipment housed in temporary shelters against weather. During 2018 the new, weatherproof, transportable cabinets will be introduced, to allow for flexible deployment, with a combination of generators and battery power supplies. We hope to see international users coming forward for collaborative trials.

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